A NEW MODE SWITCHING CONTROL FOR FAST SETTLING AND HIGH PRECISION POSITIONING

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INTRODUCTION

Recently, with rapid development of digital media like semiconductor and large flat panel display, the manufacturing equipment is required to have high precision over large travel range. Moreover it should have high product throughput. To achieve high product throughput, a controller should perform fast point-to-point motion and high precision positioning after settling in spite of external disturbances or residual vibrations. A time-optimal control plays an important role in achieving high speed point-to-point motion [2]. A conventional time-optimal control algorithm like Bang-bang control has a drawback of chattering. A proximate time-optimal servomechanism (PTOS) can achieve fast settling without chattering [2]-[3]. To improve positioning accuracy after settling, robust tracking controller such as TDC, PID, H_∞, LQG, LTR and RPT should be used to increase control bandwidth and to suppress disturbances around the target position [2],[5]-[9]. A mode switching control (MSC) enables both the fast point-to-point motion and the high precision positioning. In the conventional MSC, the track seeking mode is switched to the track following mode under certain conditions. One of the design problems for MSC is the method of switching between controllers. This design problem has not yet been completely resolved, and many approaches have been tried so far [9]-[12]. Yamaguchi proposed a method called initial value compensation (IVC) to reduce the impact of the initial value during mode switching [10]-[12]. Here the initial value means the values of the states at the instance of mode switching. This method gives an additional input to a controller at the instance of mode switching. The additional input, which is an impulse response of the initial state variables of the plant at mode switching, is designed to change transfer functions from the initial variables to the controlled variables, such as position, into better ones with assigned poles [10]-[12]. The IVC algorithm, however, is highly sensitive to plant and controller model. To make smooth mode switching without transient response, we should calculate control input of tracking controller using the information of state variables such as position, velocity and control input of the point-to-point controller at the instance of mode switching. The time-delay control (TDC) algorithm uses time-delayed information (the values of the control inputs and derivatives of state variables at the previous time step) to estimate both the plant dynamics (nominal part) and the uncertainties – parameter variation, external disturbances and unknown dynamics [5]-[6]. Hence, the use of time-delayed information eliminates the need for initial value compensation during mode switching. In this paper, to improve settling and positioning performance, we propose a new MSC design, which uses PTOS for fast point-to-point motion and TDC for robust tracking.

MODE SWITCHING CONTROL ALGOTIGHM

We propose a new MSC algorithm in which the point-to-point motion is controlled by a PTOS and the tracking mode is controlled by a TDC. Each controller of these two modes can be designed independently.

A. Proximate time optimal servomechanism (PTOS)

The point-to-point motion is a time-optimal control problem. In this subsection, we recall the conventional PTOS design for VCM stage characterized by

$$\dot{x} = Ax + Bu = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ a \end{bmatrix} u, \qquad x = \begin{bmatrix} y \\ v \end{bmatrix} \tag{1}$$

where x is the state vector which consists of the position y and the velocity v of the VCM stage and u is control input. Let r be the desired target position, $e=r-y$ be the position error. The PTOS control input is given by

$$u = u_{max} sat\left(\frac{k_2[f(e) - v]}{u_{max}} \right) \tag{2}$$

where the function $f(\cdot)$ is given by

$$f(e)=\begin{cases}\dfrac{k_1}{k_2}e & |e|\le y_l\\ \operatorname{sgn}(e)\left[\sqrt{2a\alpha u_{max}|e|}-\dfrac{u_{max}}{k_2}\right] & |e|>y_l\end{cases} \quad (3)$$

Here the control parameter k_2 is determined from the acceleration discount factor α $(0<\alpha<1)$, and the closed loop poles during point-to-point motion control mode with the following continuity constraints:

$$k_2=\sqrt{\frac{2k_1}{\alpha a}} \quad \text{and} \quad y_l=\frac{u_{max}}{k_1} \quad (4)$$

where y_l is the boundary region in which the PTOS operates as a PD controller. The PTOS uses a smooth nonlinear velocity profile by introducing the acceleration discount factor α. The discounted deceleration, however, makes the rising time longer than that of the original time-optimal controller.

B. Time-delay control (TDC)

The TDC is known to be a tracking control algorithm which is robust to system uncertainties and disturbances. It uses time-delayed information to estimate both the plant dynamics and the uncertainties. The control input is given by

$$u(t)=u(t-t_s)-\bar{M}\ddot{x}(t-t_s)+\bar{M}\{\ddot{x}_d(t)+K_D\dot{e}(t)+K_Pe(t)\} \quad (5)$$

where x_d is the reference input, x is the position of the stage, t_s is sampling period, $\bar{M}$ is the estimation value of the stage mass, K_P and K_D are control parameters. Let r be the desired position, $e=r-y$ be the position error. Then, position error is decayed to zero according to error dynamics given by

$$\ddot{e}(t)+K_D\dot{e}(t)+K_Pe(t)=0 \quad (6)$$

C. Mode switching control (MSC)

Fig. 1. represents the timing diagram of the proposed MSC. During the position error is larger than switching boundary E_{SW}, the MSC operates as the PTOS to achieve fast point-to-point motion. When the position error is equal to E_{SW}, the controller mode is switched from the PTOS to the TDC. At the instance of mode switching, the TDC calculates control input using position, velocity and previous control input of the PTOS. After mode switching, the MSC operates as the TDC to achieve high precision positioning.

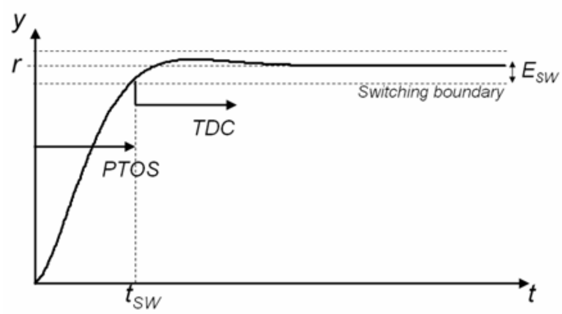


FIGURE 1. Timing diagram of the proposed MSC..

The control input of the MSC is calculated as follows

1) If $|r-y|>E_{SW}$, the MSC operates as the PTOS and control input is given by

$$u_{MSC}=u_{PTOS}=u_{max}sat\left(\frac{k_2[f(e)-v]}{u_{max}}\right) \quad (7)$$

where the function $f(\cdot)$ is given by

$$f(e)=\begin{cases}\dfrac{k_1}{k_2}e & |e|\le y_l\\ \operatorname{sgn}(e)\left[\sqrt{2a\alpha u_{max}|e|}-\dfrac{u_{max}}{k_2}\right] & |e|>y_l\end{cases} \quad (8)$$

2) If $|r-y|=E_{SW}$, the controller mode is switched from the PTOS to the TDC. At the instance of mode switching, the control input is given by

$$\begin{aligned}u_{MSC}(t_{SW})=u_{TDC}(t_{SW})&=u_{TDC}(t_{SW}-t_s)-\bar{M}\ddot{x}(t_{SW}-t_s)\\&+\bar{M}\{\ddot{x}_d(t_{SW})+K_D\dot{e}(t_{SW})+K_Pe(t_{SW})\}\end{aligned} \quad (9)$$

where t_s means sampling period, t_{sw} is the time at which mode switches. Here, the control input of the PTOS is substituted for the previous one of the TDC as follows

$$u_{TDC}(t_{SW}-t_s)=u_{PTOS}(t_{SW}-t_s) \quad (10)$$

This guarantees smooth mode switching. Then, the control input of the MSC at the instance of mode switching is given by

$$\begin{aligned}u_{MSC}(t_{SW})=u_{TDC}(t_{SW})&=u_{PTOS}(t_{SW}-t_s)-\bar{M}\ddot{x}(t_{SW}-t_s)\\&+\bar{M}\{\ddot{x}_d(t_{SW})+K_D\dot{e}(t_{SW})+K_Pe(t_{SW})\}\end{aligned} \quad (11)$$

3) If $|r-y|<E_{SW}$, the MSC operates as TDC and the control input is given by

$$\begin{aligned}u_{MSC}(t)=u_{TDC}(t)&=u_{TDC}(t-t_s)-\bar{M}\ddot{x}(t-t_s)\\&+\bar{M}\{\ddot{x}_d(t)+K_D\dot{e}(t)+K_Pe(t)\}\end{aligned} \quad (12)$$

EXPERIMENTAL SETUP

To verify the effectiveness of the proposed MSC algorithm, we compared the results of applying the MSC algorithm to the dual-stage with the corresponding results of the conventional PTOS. The implemented dual-stage is shown in Fig. 2. It consists of the coarse stage which is actuated by linear motor for large travel range and the fine stage which is actuated by voice coil motor (VCM) for high speed and high precision motion. The position of linear motor stage is measured by linear encoder and that of VCM stage is measured by laser interferometer (HP10885) with resolution of 5nm. Both stages are guided by air bearing to obtain smooth and fast motion without friction.

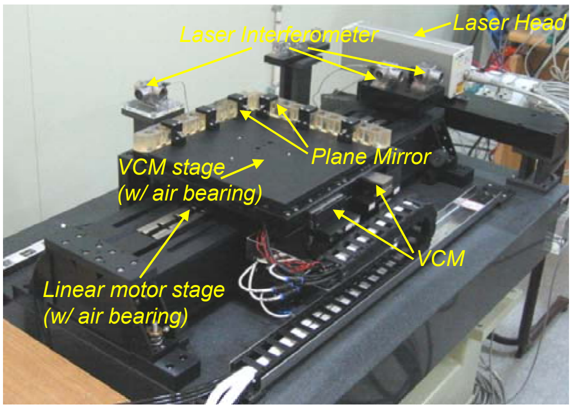


FIGURE 2. Long-range high-precision dual stage..

The performance of the dual stage is mainly determined by the fine VCM stage. It is quite conventional to approximate the dynamics of the VCM actuator by a second order model as

$$G_{VCM}(s) = \frac{X}{I}(s) = \frac{a}{s^2} \tag{13}$$

where X is the position of the stage, I is the current input and $a=K_F/M$ is the acceleration constant, with K_F being the force constant and M being the mass of the VCM stage. The parameters of the VCM stage are shown in Table 1. The control algorithm was implemented on a dSPACE real-time DSP (ds1105) control system with sampling frequency of 10 kHz.

TABLE 1. System Parameters

Parameters	Quantity	Unit
Mass of VCM stage, M	27.4	kg
Force constant, K_F	36.2	$N \cdot A^{-1}$
Acceleration coefficient, a	1.323	$m \cdot s^{-2} \cdot A^{-1}$
Maximum current, U_{max}	4	A
Sampling period, t_s	100	μs

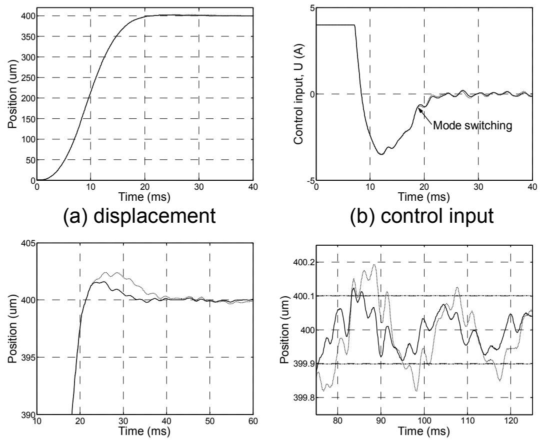
EXPERIMENTAL RESULTS

The proposed MSC algorithm given by (7)-(12) was implemented on the fine VCM stage. The results were compared with those of the conventional PTOS controller given by (2). The MSC and the PTOS were tuned to have the best performance. For 400 um and 10 mm step input, we adjusted the control parameters of the PTOS to $\alpha=0.9$, $k_1=10^5$ and $k_2=409$ and that of the TDC to $\bar{M}=0.75$, $K_P=10^5$ and $K_D=520$. The switching boundary E_{SW} was set to 15 um based on the simulation results. In particular, we focused on the following performance.

1) settling time at which position error becomes less than 100 nanometer to characterize the point-to-point motion (absolute error bound is important in precision measurement system)

2) standard deviation of the position error during 200 ms after settling to characterize positioning error.

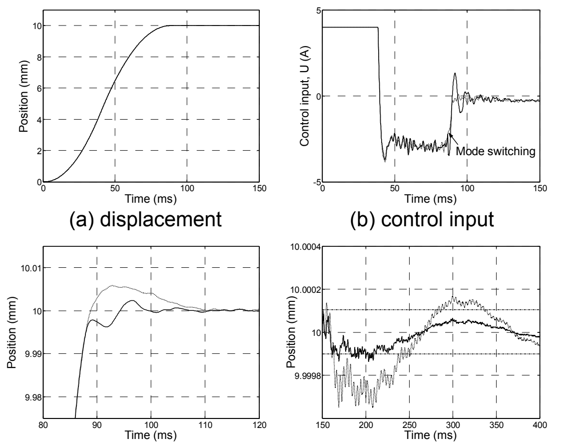
Fig. 3. shows 400 um step response. As shown in Fig. 3(c) and 3(d), the MSC has faster settling performance and less positioning error. Fig. 4. shows 10 mm step response. As illustrated in Fig. 4(c) and 4(d), the MSC achieved faster settling and better positioning performance. Fig. 3(b) and 4(b) illustrate the control input of 400 um and 10 mm step response, respectively. At the instance of mode switching, the transient response in control input is negligible, which leads smooth mode switching. The experimental results with the PTOS and the MSC are compared in Table 2. As shown in Table 2, 100 nm settling time and positioning error were highly improved with the proposed MSC.



(a) displacement (b) control input

(c) displacement (zoom) (d) displacement (zoom)

FIGURE 3. 400 um step response. (dotted : PTOS, solid : MSC)



(a) displacement (b) control input

(c) displacement (zoom) (d) displacement (zoom)

FIGURE 4. 10 mm step response. (dotted : PTOS, solid : MSC)

TABLE 2. Experiment results : settling time and positioning error.

	Performance	PTOS	MSC	Improvement with the MSC
400 um	100 nm settling time	140 ms	86 ms	39 %
	Positioning error (1σ)	12 nm	6 nm	45 %
10 mm	100 nm settling time	323 ms	218 ms	33 %
	Positioning error (1σ)	22 nm	8 nm	62 %

CONCLUSION

We proposed in this paper a new MSC algorithm to achieve both the fast point-to-point motion and precise positioning after settling. Combination of the PTOS and the TDC enables smooth mode switching without any compensation of initial value. Since the TDC calculates control input using previous one of the PTOS at the instance of mode switching. The experimental results show that proposed MSC has a significant improvement in settling time and precise positioning. The proposed MSC is simple to design and can be easily applied to other servomechanism like hard disk drives that requires both the fast settling and high precision positioning.

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